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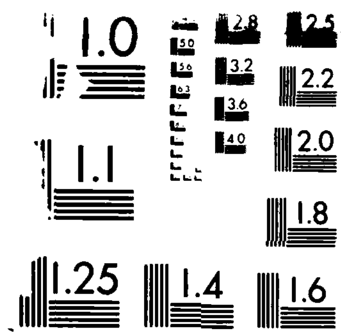

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Petersen Multipliers for Several SEU Environment Models

D. L. CHENETTE
Space Sciences Laboratory
Laboratory Operations
The Aerospace Corporation
El Segundo, CA 90245

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Several published models for the interplanetary heavy-ion environment resulting from galactic cosmic rays and solar-flare-accelerated ions are described. These models are used to calculate linear energy transfer (LET) spectra behind 1 g cm^{-2} (150 mils) of aluminum shielding. Appropriate parameters (multipliers) are deduced from these spectra for use in the "Suggested Single-Event Upset Figure of Merit" calculation described by Petersen et al. (1983). The results of this study are compared to the suggestions of E. C. Smith, and the differences between the two are discussed.

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I. INTRODUCTION

Since the mid-1970s, when it was recognized that heavily ionizing energetic charged particles were the cause of logic and memory upsets in integrated circuits, these "single-event upsets" have been the subject of considerable research and analysis. The mechanism for producing single-event upsets is well understood. Energetic heavy ions can cause these upsets because they can deposit more energy, via ionization, than the energy of the signal representing the information stored in a logic cell of an integrated circuit. Much work has been devoted to characterizing the sensitivity of various specific integrated circuits and logic families, and to determining methods for estimating the rate at which a given device may be upset by the radiation environment in which it operates.

Tests to determine the sensitivity of a given device seek to measure two characteristics: (1) a threshold energy deposit, or critical charge, which is the minimum amount of energy that must be deposited in a sensitive region to upset the device; and (2) the size of the sensitive region. (Deposited energy and charge are related by a constant of proportionality equal to 3.6 eV per charge for silicon.) The rate at which a device may be upset is equal to the flux of particles having a sufficient ionization and pathlength through the sensitive volume such that the product (ionization × pathlength) is greater than the critical charge. Thus the device upset rate depends on an integral over a pathlength distribution of the spectrum of particle ionization. This particle ionization spectrum is also called the linear energy transfer, or LET, spectrum. The LET spectrum is determined from the composition and energy spectra of all species of ionizing particles in the environment, together with the thickness of material surrounding a given device which shields it from this radiation environment.

Integrating the LET spectrum over a pathlength distribution is a straightforward task, but not a particularly simple one. Recognizing the need for a "quick and dirty" approach to this problem, Petersen et al. (1983) have proposed a "single-event upset figure of merit" which yields an estimated

upset rate for any device, given its critical charge threshold and sensitive area. This "figure of merit" calculation incorporates approximations to both the geometry of the sensitive region and the form of the LET spectrum, so that the integral of (LET × pathlength) takes a particularly simple form. To derive their "figure-of-merit," Petersen et al. adopted an approximation to the differential flux intensity of the LET spectrum by assuming that the differential particle flux of particles with a given LET was proportional to the -3 power of the LET (equivalent to the integral flux, $F = A \times (\mathrm{LET})^{-2}$, for some constant A). The result of these approximations is that the "Petersen figure of merit" upset rate for any device may be written as

$$R = K(S/L_c^2) \quad \text{(approximate)}$$

where R is the figure-of-merit upset rate; S is the surface area of the sensitive region; L_c is the device LET threshold; and K is a constant proportional to A, the intensity of the LET spectrum.

Petersen et al. proposed that their figure of merit be based on a specific model of the heavy-ion environment, the "90% worst case" environment defined by Adams et al. (1981). As the name implies, this model was defined so that the natural fluxes of heavy ions from the galactic cosmic rays and from solar and interplanetary acceleration events could be expected to exceed the model for no more than 10% of any large number of randomly selected, short periods of time.

Given this environment, Petersen et al. approximated the model differential LET spectrum [with LET measured in ($\mathrm{MeV/g/cm^2}$)]:

$$f\text{(differential flux)} = 5.8 \times 10^8\ (\mathrm{LET})^{-3}\ \text{particles}/(\mathrm{cm}^2\ \text{day})(\mathrm{MeV/g/cm}^2)$$

which is equivalent to the integral LET spectrum:

$$F\ \text{(integral flux)} = 2.9 \times 10^8\ (\mathrm{LET})^{-2}\ \text{particles}/(\mathrm{cm}^2\ \text{day})$$

and determined that the constant K should therefore have the value

$$K = 5 \times 10^{-10} \text{ (upsets/cell/day)} \times (\text{pC}/\mu\text{m})^2/\mu\text{m}^2$$

(for S in μm^2 and for L_c in picocoulombs per μm). (In another system of units, the constant in the equation for F, above, takes the value 0.145 $(m^2\text{-s-sr})^{-1}$, with LET expressed in MeV/μm. These are the units used in the tables attached to this report.)

Petersen et al. specifically note that this use of a reference environment and the errors inherent in approximating the LET spectrum as a power law over a wide range of LET do not permit accurate predictions of absolute upset rates to be made. However, the results of their figure-of-merit calculation may be useful in predicting relative upset rates of various devices, given estimates or measurements for S and L_c.

The Petersen figure of merit is appealing because of its simplicity. Thus there is a significant impetus to apply this method to other reference environments. In the rest of this report, a number of other environment models are described. LET spectra are calculated for each of these environments, and revised values for K are defined, as appropriate, for each environment model.

II. REFERENCE ENVIRONMENTS FOR THE CALCULATION OF HEAVY-ION LET SPECTRA

The major sources of energetic, heavily ionizing particles are the galactic cosmic rays and energetic ions accelerated during solar flare events. Time-intensity profiles, energy spectra, and the composition of these two populations of particles are sufficiently different to warrant separate treatment. Galactic cosmic rays are continually present; their intensities vary relatively slowly over the 11-year solar cycle, declining as solar activity increases and recovering once again during periods of minimum solar activity. In contrast, energetic solar ions appear near earth as the result of impulsive solar flare events. Their intensities vary rapidly over periods of a few hours to days, and the peak intensity of the heavy-ion flux from a single event varies greatly from flare to flare.

Adams et al. (1981) have made a comprehensive summary of the results of several decades of research on the fluxes of the galactic cosmic rays and of solar flare particle events. From this summary they have derived a set of model environments that describe the interplanetary heavy-ion flux and fluence distributions that may be expected under a wide variety of conditions. These models have since become standards for use in the specification of system performance and immunity from single-event upsets.

The data base of energetic heavy-ion events that was available to Adams et al. was severely limited, however, and Chenette and Dietrich (1984) have published a summary of solar flare event characteristics over the solar cycle from 1973 to 1984, in an attempt to fill this gap.

The following environment models have been selected to expand the Petersen figure of merit method:

1. "Galactic": the solar minimum galactic cosmic ray spectrum described by Adams et al. (1981).

2. "IMP-8": a solar flare heavy-ion spectrum based on the 24 September, 1977 solar flare event as described by Chenette and Dietrich (1984), and measured by an experiment aboard the satellite IMP-8,

3. "Ordinary": the Adams et al. "ordinary" solar flare model,

4. the "90% worst case" flare environment model of Adams et al., and

5. "AL": the anomalously large flare model of Adams et al.

Each of these model environments is described in terms of both the instantaneous peak particle flux and the total fluence of particles expected (flux integrated over time). In the case of the galactic cosmic ray model, the total annual fluence during a year near solar minimum conditions is compared to the total fluence for a single solar flare event. Additionally, for the solar flare models, two kinds of particle composition are studied: "normal" composition and heavy-ion-enriched composition (see the descriptions of each model for details).

Figures 1 through 4 and Tables 1 through 4 summarize the integral LET spectra that result from these models. In each case the LET spectrum was calculated assuming a passive shield of 1 g/cm^2 (equivalent to 150 mils of aluminum). Figures 1 and 2 and Tables 1 and 2 give integral LET spectra corresponding to the peak event flux for normal (1) and heavy-ion-enriched (2) composition. Figures 3 and 4 and Tables 3 and 4 give integral LET fluence spectra for each event, assuming normal (3) and heavy-ion-enriched (4) composition. (Heavy-ion enrichment does not apply to the galactic cosmic ray environment models.) The results at LET < 8 MeV/μm are poorer approximations to the true LET spectrum expected in space. This is because (1) the abundances of the elements that have such large LETs are only poorly known, and (2) at these large LETs, as a result of the small fluxes and fluences, other factors (e.g., nuclear interactions) may dominate the incident primary-particle flux.

Additionally, in Tables 5 through 8 the integral LET spectra in Tables 1 through 4 are presented as ratios to the Petersen environment. The values in these tables may be used to multiply the Petersen environment directly to obtain the LET spectrum of each of Tables 1 through 4. For the fluence models reported in Tables 6 and 8, the multiplier is divided by 1 day (86,400 sec). The results that appear in the tables may then be read as an equivalent number of days of exposure to the Petersen environment or as a multiplier to the

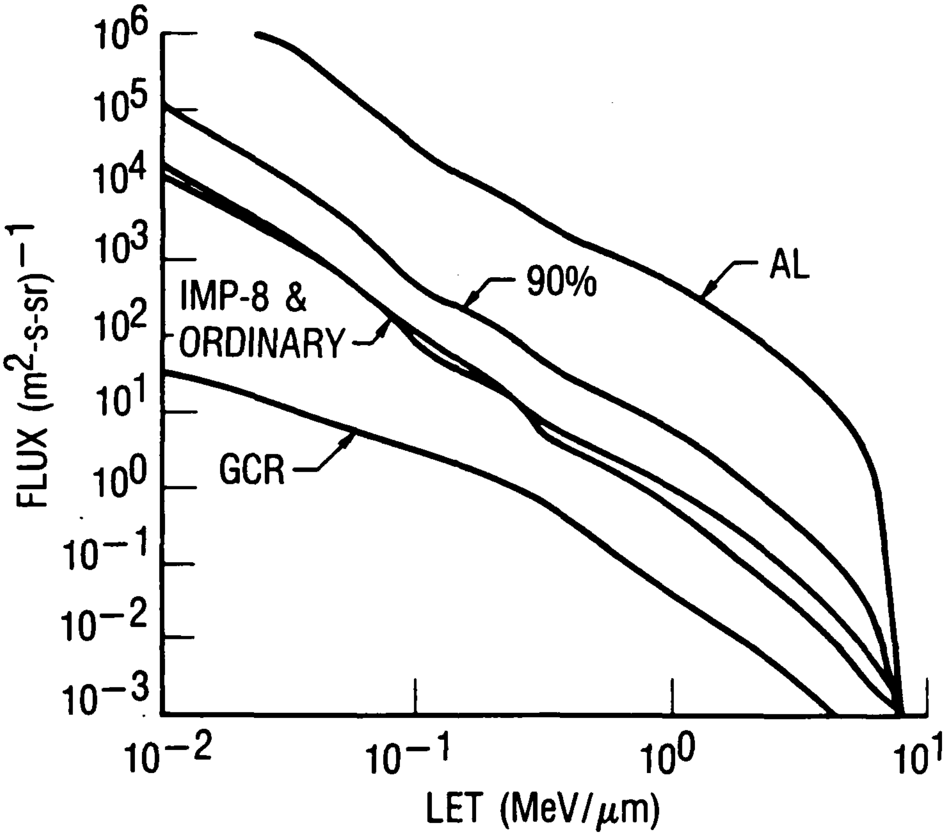

Fig. 1. Peak Event Flux LET Spectra for Several Solar Flare Models Assuming Normal Composition, and the Galactic Cosmic Ray (GCR) Model LET Spectrum at Solar Minimum

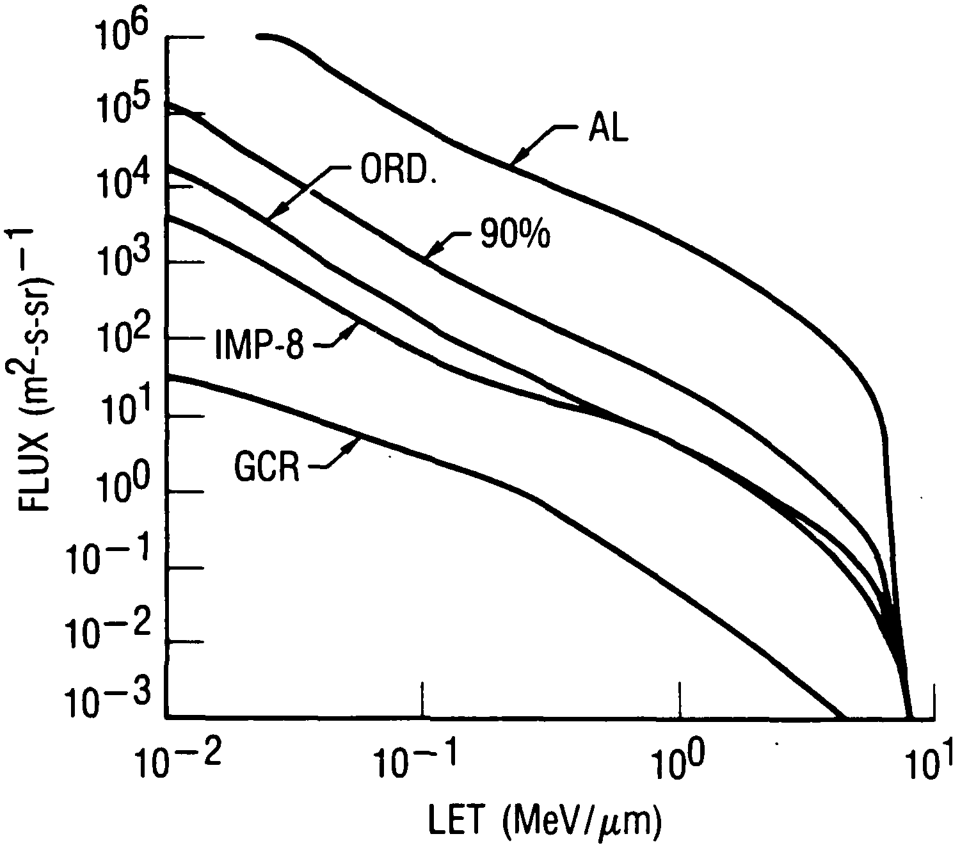

Fig. 2. Peak Event Flux LET Spectra for Several Solar Flare Models Assuming Heavy-Ion Enrichment, and the Galactic Cosmic Ray (GCR) Model LET Spectrum at Solar Minimum

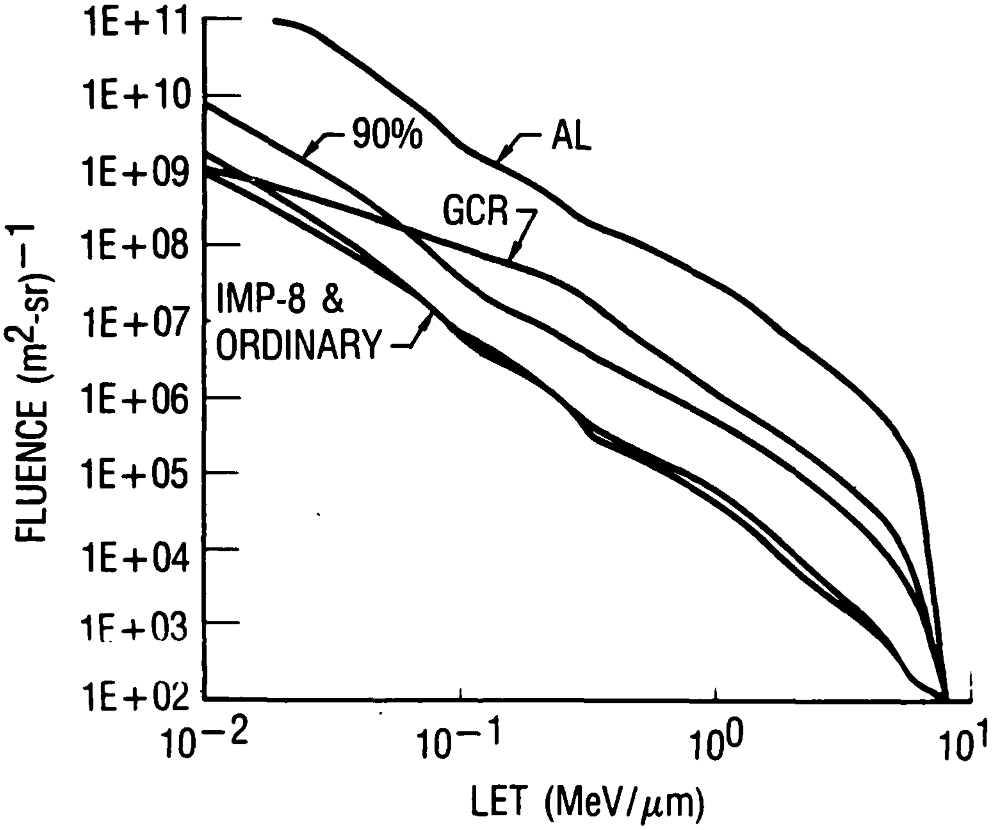

Fig. 3. Total Event Fluence LET Spectra for Several Solar Flare Models Assuming Normal Solar Composition, and the Annual Galactic Cosmic Ray (GCR) LET Fluence Spectrum during Solar Minimum

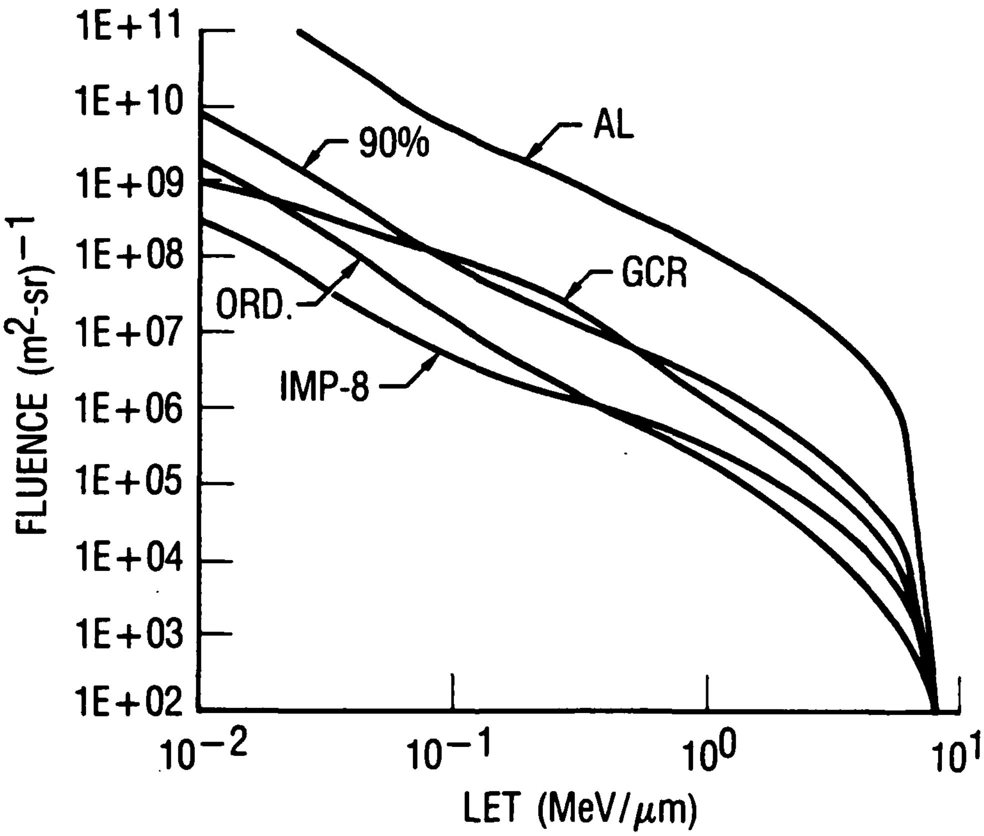

Fig. 4. Total Event Fluence LET Spectra for Several Solar Flare Models Assuming Heavy-Ion Enrichment, and the Annual Galactic Cosmic Ray (GCR) Model LET Fluence Spectrum during Solar Minimum

Table 1. Heavy-Ion LET Spectra for Several Environment Models.
Normal composition - peak event flux - 1 g/cm^2 shielding.

Integral Particle Flux above LET Threshold $(m^2\text{-}s\text{-}sr)^{-1}$

LET (MeV/μm)	Galactic	IMP-8	Ordinary	90% WC	AL
1.000E-02	3.387E+01	1.292E+04	1.807E+04	1.191E+05	7.223E+06
1.339E-02	2.663E+01	7.975E+03	1.026E+04	6.727E+04	4.077E+06
1.793E-02	2.038E+01	4.789E+03	5.715E+03	3.729E+04	2.262E+06
2.400E-02	1.531E+01	2.757E+03	3.104E+03	2.012E+04	1.221E+06
3.213E-02	1.100E+01	1.529E+03	1.654E+03	1.065E+04	6.476E+05
4.302E-02	8.000E+00	8.085E+02	8.381E+02	5.366E+03	3.280E+05
5.759E-02	5.851E+00	4.184E+02	4.129E+02	2.631E+03	1.625E+05
7.710E-02	4.204E+00	2.169E+02	2.059E+02	1.307E+03	8.186E+04
1.032E-01	2.986E+00	9.370E+01	6.896E+01	4.353E+02	2.846E+04
1.382E-01	2.161E+00	5.438E+01	4.297E+01	2.716E+02	1.789E+04
1.850E-01	1.542E+00	2.946E+01	2.535E+01	1.602E+02	1.073E+04
2.477E-01	1.029E+00	1.492E+01	1.434E+01	9.028E+01	6.203E+03
3.317E-01	5.607E-01	4.608E+00	6.405E+00	3.990E+01	2.943E+03
4.440E-01	2.822E-01	2.799E+00	4.020E+00	2.484E+01	1.883E+03
5.945E-01	1.438E-01	1.674E+00	2.492E+00	1.519E+01	1.201E+03
7.959E-01	7.378E-02	9.841E-01	1.541E+00	9.248E+00	7.643E+02
1.066E+00	3.816E-02	5.509E-01	9.207E-01	5.453E+00	4.631E+02
1.427E+00	1.963E-02	2.705E-01	4.992E-01	2.903E+00	2.526E+02
1.910E+00	9.803E-03	1.003E-01	2.213E-01	1.234E+00	1.166E+02
2.557E+00	4.874E-03	4.706E-02	1.083E-01	5.946E-01	5.792E+01
3.424E+00	2.165E-03	1.993E-02	4.442E-02	2.370E-01	2.481E+01
4.584E+00	9.445E-04	8.633E-03	1.931E-02	1.019E-01	1.096E+01
6.137E+00	1.961E-04	2.311E-03	5.183E-03	2.736E-02	2.944E+00
8.216E+00	8.279E-08	6.561E-07	9.227E-07	4.516E-06	6.390E-04

Table 2. Heavy-Ion LET Spectra for Several Environment Models. Worst-case composition - peak event flux - 1 g/cm^2 shielding

LET (MeV/μm)	Integral Particle Flux Above LET Threshold (m^2-s-sr)$^{-1}$				
	Galactic	IMP-8	Ordinary	90% WC	AL
1.000E-02	3.387E+01	4.294E+03	1.964E+04	1.299E+05	7.894E+06
1.339E-02	2.663E+01	2.703E+03	1.141E+04	7.521E+04	4.574E+06
1.793E-02	2.038E+01	1.658E+03	6.508E+03	4.265E+04	2.603E+06
2.400E-02	1.531E+01	9.788E+02	3.626E+03	2.356E+04	1.443E+06
3.213E-02	1.100E+01	5.628E+02	1.992E+03	1.282E+04	7.912E+05
4.302E-02	8.000E+00	3.159E+02	1.060E+03	6.760E+03	4.236E+05
5.759E-02	5.851E+00	1.801E+02	5.663E+02	3.582E+03	2.300E+05
7.710E-02	4.204E+00	1.073E+02	3.168E+02	1.990E+03	1.313E+05
1.032E-01	2.986E+00	6.130E+01	1.500E+02	9.352E+02	6.478E+04
1.382E-01	2.161E+00	4.287E+01	1.013E+02	6.322E+02	4.425E+04
1.850E-01	1.542E+00	2.998E+01	6.536E+01	4.069E+02	2.910E+04
2.477E-01	1.029E+00	2.148E+01	4.091E+01	2.531E+02	1.866E+04
3.317E-01	5.607E-01	1.491E+01	2.294E+01	1.401E+02	1.095E+04
4.440E-01	2.822E-01	1.158E+01	1.495E+01	9.026E+01	7.328E+03
5.945E-01	1.438E-01	8.681E+00	9.667E+00	5.736E+01	4.910E+03
7.959E-01	7.378E-02	6.116E+00	6.254E+00	3.644E+01	3.277E+03
1.066E+00	3.816E-02	3.991E+00	3.909E+00	2.248E+01	2.066E+03
1.427E+00	1.963E-02	2.408E+00	2.243E+00	1.273E+01	1.180E+03
1.910E+00	9.803E-03	1.343E+00	1.096E+00	6.031E+00	5.897E+02
2.557E+00	4.874E-03	7.342E-01	5.562E-01	3.028E+00	3.019E+02
3.424E+00	2.165E-03	3.751E-01	2.423E-01	1.290E+00	1.359E+02
4.584E+00	9.445E-04	1.789E-01	1.075E-01	5.675E-01	6.103E+01
6.137E+00	1.961E-04	4.922E-02	2.891E-02	1.526E-01	1.641E+01
8.216E+00	8.279E-08	8.421E-05	9.227E-07	4.516E-06	6.390E-04

Table 3. Heavy-Ion LET Spectra for several environment models.
Normal composition - event fluence - 1 g/cm^2 shielding.

LET (MeV/μm)	Integral Particle Fluence Above LET Threshold $(m^2\text{-}sr)^{-1}$				
	Galactic	IMP-8	Ordinary	90% WC	AL
1.000E-02	1.069E+09	9.306E+08	1.669E+09	7.499E+09	4.976E+11
1.339E-02	8.402E+08	5.742E+08	9.464E+08	4.243E+09	2.787E+11
1.793E-02	6.430E+08	3.448E+08	5.257E+08	2.358E+09	1.533E+11
2.400E-02	4.831E+08	1.985E+08	2.836E+08	1.279E+09	8.210E+10
3.213E-02	3.472E+08	1.101E+08	1.497E+08	6.819E+08	4.329E+10
4.302E-02	2.525E+08	5.821E+07	7.496E+07	3.469E+08	2.187E+10
5.759E-02	1.847E+08	3.013E+07	3.627E+07	1.725E+08	1.086E+10
7.710E-02	1.327E+08	1.562E+07	1.764E+07	8.729E+07	5.524E+09
1.032E-01	9.423E+07	6.746E+06	5.453E+06	3.064E+07	1.990E+09
1.382E-01	6.818E+07	3.915E+06	3.325E+06	1.934E+07	1.272E+09
1.850E-01	4.866E+07	2.121E+06	1.908E+06	1.160E+07	7.705E+08
2.477E-01	3.247E+07	1.074E+06	1.037E+06	6.697E+06	4.486E+08
3.317E-01	1.769E+07	3.318E+05	4.061E+05	3.171E+06	2.170E+08
4.440E-01	8.904E+06	2.015E+05	2.498E+05	2.004E+06	1.359E+08
5.945E-01	4.539E+06	1.206E+05	1.499E+05	1.255E+06	8.383E+07
7.959E-01	2.328E+06	7.086E+04	8.890E+04	7.847E+05	5.158E+07
1.066E+00	1.204E+06	3.966E+04	5.097E+04	4.729E+05	3.070E+07
1.427E+00	6.196E+05	1.948E+04	2.602E+04	2.592E+05	1.656E+07
1.910E+00	3.094E+05	7.218E+03	1.004E+04	1.179E+05	7.251E+06
2.557E+00	1.538E+05	3.388E+03	4.666E+03	5.818E+04	3.532E+06
3.424E+00	6.833E+04	1.435E+03	1.740E+03	2.430E+04	1.437E+06
4.584E+00	2.981E+04	6.216E+02	7.312E+02	1.063E+04	6.225E+05
6.137E+00	6.188E+03	1.664E+02	1.961E+02	2.854E+03	1.671E+05
8.216E+00	2.613E+00	4.724E-02	2.796E-02	5.349E-01	2.906E+01

Table 4. Heavy-Ion LET Spectra for Several Environment Models.
Worst-case composition - event fluence - 1 g/cm^2 shielding.

LET	Integral Particle Fluence above LET Threshold $(m^2\text{-}sr)^{-1}$				
(MeV/µm)	Galactic	IMP-8	Ordinary	90% WC	AL
1.000E-02	1.069E+09	3.092E+08	1.813E+09	8.184E+09	5.486E+11
1.339E-02	8.402E+08	1.947E+08	1.054E+09	4.741E+09	3.152E+11
1.793E-02	6.430E+08	1.194E+08	5.986E+08	2.699E+09	1.774E+11
2.400E-02	4.831E+08	7.047E+07	3.298E+08	1.504E+09	9.736E+10
3.213E-02	3.472E+08	4.052E+07	1.781E+08	8.295E+08	5.297E+10
4.302E-02	2.525E+08	2.274E+07	9.240E+07	4.463E+08	2.828E+10
5.759E-02	1.847E+08	1.297E+07	4.755E+07	2.432E+08	1.542E+10
7.710E-02	1.327E+08	7.725E+06	2.533E+07	1.396E+08	8.928E+09
1.032E-01	9.423E+07	4.414E+06	1.090E+07	6.947E+07	4.551E+09
1.382E-01	6.818E+07	3.086E+06	7.187E+06	4.755E+07	3.148E+09
1.850E-01	4.866E+07	2.159E+06	4.496E+06	3.115E+07	2.076E+09
2.477E-01	3.247E+07	1.547E+06	2.701E+06	1.985E+07	1.325E+09
3.317E-01	1.769E+07	1.073E+06	1.380E+06	1.153E+07	7.722E+08
4.440E-01	8.904E+06	8.337E+05	8.739E+05	7.587E+06	5.015E+08
5.945E-01	4.539E+06	6.250E+05	5.409E+05	4.971E+06	3.224E+08
7.959E-01	2.328E+06	4.404E+05	3.326E+05	3.255E+06	2.074E+08
1.066E+00	1.204E+06	2.874E+05	1.991E+05	2.049E+06	1.292E+08
1.427E+00	6.196E+05	1.734E+05	1.088E+05	1.184E+06	7.386E+07
1.910E+00	3.094E+05	9.666E+04	4.782E+04	5.883E+05	3.576E+07
2.557E+00	1.538E+05	5.286E+04	2.334E+04	3.005E+05	1.810E+07
3.424E+00	6.833E+04	2.701E+04	9.434E+03	1.327E+05	7.833E+06
4.584E+00	2.981E+04	1.288E+04	4.071E+03	5.917E+04	3.466E+06
6.137E+00	6.188E+03	3.544E+03	1.094E+03	1.591E+04	9.321E+05
8.216E+00	2.613E+00	6.063E+00	2.796E-02	5.349E-01	2.906E+01

Table 5. Heavy-Ion LET Spectra; Ratios to Petersen Environment. Normal composition - peak event flux - 1 g/cm^2 shielding.

LET (MeV/μm)	Ratio of Environment to Petersen Environment				
	Galactic	IMP-8	Ordinary	90% WC	AL
1.000E-04	2.336E-02	8.913E+00	1.246E+01	8.210E+01	4.981E+03
1.792E-04	3.291E-02	9.859E+00	1.268E+01	8.315E+01	5.039E+03
3.213E-04	4.515E-02	1.061E+01	1.266E+01	8.262E+01	5.011E+03
5.759E-04	6.080E-02	1.095E+01	1.233E+01	7.990E+01	4.850E+03
1.032E-03	7.832E-02	1.089E+01	1.178E+01	7.581E+01	4.610E+03
1.850E-03	1.021E-01	1.032E+01	1.069E+01	6.847E+01	4.185E+03
3.317E-03	1.338E-01	9.571E+00	9.443E+00	6.017E+01	3.716E+03
5.945E-03	1.724E-01	8.892E+00	8.443E+00	5.359E+01	3.356E+03
1.066E-02	2.194E-01	6.886E+00	5.068E+00	3.199E+01	2.091E+03
1.910E-02	2.846E-01	7.162E+00	5.660E+00	3.577E+01	2.357E+03
3.424E-02	3.641E-01	6.955E+00	5.986E+00	3.782E+01	2.533E+03
6.137E-02	4.354E-01	6.315E+00	6.068E+00	3.821E+01	2.625E+03
1.100E-01	4.253E-01	3.496E+00	4.859E+00	3.027E+01	2.233E+03
1.972E-01	3.837E-01	3.806E+00	5.467E+00	3.378E+01	2.561E+03
3.534E-01	3.506E-01	4.081E+00	6.073E+00	3.703E+01	2.928E+03
6.335E-01	3.223E-01	4.299E+00	6.730E+00	4.040E+01	3.339E+03
1.136E+00	2.988E-01	4.314E+00	7.210E+00	4.270E+01	3.627E+03
2.035E+00	2.756E-01	3.797E+00	7.008E+00	4.075E+01	3.546E+03
3.648E+00	2.466E-01	2.522E+00	5.568E+00	3.104E+01	2.933E+03
6.539E+00	2.198E-01	2.122E+00	4.883E+00	2.681E+01	2.612E+03
1.172E+01	1.750E-01	1.611E+00	3.591E+00	1.915E+01	2.006E+03
2.101E+01	1.369E-01	1.251E+00	2.797E+00	1.477E+01	1.588E+03
3.766E+01	5.092E-02	6.003E-01	1.346E+00	7.106E+00	7.647E+02
6.750E+01	3.854E-05	3.054E-04	4.295E-04	2.102E-03	2.975E-01
Maximum:	0.44	11	13	83	5000

Table 6. Heavy-Ion LET Spectra; Ratios to Petersen Environment.
Worst-case composition - peak event flux - 1 g/cm^2 shielding.

LET (MeV/μm)	Ratio of Environment to Petersen Environment: Galactic	IMP-8	Ordinary	90% WC	AL
1.000E-04	2.336E-02	2.961E+00	1.354E+01	8.958E+01	5.444E+03
1.792E-04	3.291E-02	3.342E+00	1.410E+01	9.297E+01	5.654E+03
3.213E-04	4.515E-02	3.674E+00	1.442E+01	9.452E+01	5.767E+03
5.759E-04	6.080E-02	3.888E+00	1.440E+01	9.357E+01	5.733E+03
1.032E-03	7.832E-02	4.007E+00	1.418E+01	9.125E+01	5.632E+03
1.850E-03	1.021E-01	4.031E+00	1.352E+01	8.626E+01	5.405E+03
3.317E-03	1.338E-01	4.119E+00	1.295E+01	8.193E+01	5.261E+03
5.945E-03	1.724E-01	4.399E+00	1.299E+01	8.159E+01	5.383E+03
1.066E-02	2.194E-01	4.505E+00	1.103E+01	6.873E+01	4.761E+03
1.910E-02	2.846E-01	5.646E+00	1.335E+01	8.327E+01	5.828E+03
3.424E-02	3.641E-01	7.079E+00	1.543E+01	9.607E+01	6.872E+03
6.137E-02	4.354E-01	9.092E+00	1.731E+01	1.071E+02	7.896E+03
1.100E-01	4.253E-01	1.131E+01	1.740E+01	1.062E+02	8.308E+03
1.972E-01	3.837E-01	1.575E+01	2.033E+01	1.227E+02	9.965E+03
3.534E-01	3.506E-01	2.116E+01	2.356E+01	1.398E+02	1.197E+04
6.335E-01	3.223E-01	2.672E+01	2.732E+01	1.592E+02	1.432E+04
1.136E+00	2.988E-01	3.125E+01	3.061E+01	1.761E+02	1.618E+04
2.035E+00	2.756E-01	3.380E+01	3.149E+01	1.787E+02	1.656E+04
3.648E+00	2.466E-01	3.378E+01	2.756E+01	1.517E+02	1.484E+04
6.539E+00	2.198E-01	3.311E+01	2.508E+01	1.366E+02	1.362E+04
1.172E+01	1.750E-01	3.032E+01	1.959E+01	1.043E+02	1.098E+04
2.101E+01	1.369E-01	2.592E+01	1.558E+01	8.223E+01	8.844E+03
3.766E+01	5.092E-02	1.278E+01	7.508E+00	3.964E+01	4.263E+03
6.750E+01	3.854E-05	3.920E-02	4.295E-04	2.102E-03	2.975E-01
Maximum:	0.44	34	31	180	16000

Table 7. Heavy Ion LET Spectra; Ratios to Petersen Environment.
Normal composition - event fluence - 1 g/cm^2 shielding.

LET (MeV/μm)	Exposure Equivalent to 1 Day in Petersen Environment (days)				
	Galactic	IMP-8	Ordinary	90% WC	AL
1.000E-04	2.336E-02	7.428E+00	1.332E+01	5.986E+01	3.972E+03
1.792E-04	3.291E-02	8.216E+00	1.354E+01	6.070E+01	3.988E+03
3.213E-04	4.515E-02	8.844E+00	1.348E+01	6.048E+01	3.931E+03
5.759E-04	6.081E-02	9.124E+00	1.304E+01	5.879E+01	3.774E+03
1.032E-03	7.833E-02	9.074E+00	1.234E+01	5.619E+01	3.567E+03
1.850E-03	1.021E-01	8.597E+00	1.107E+01	5.124E+01	3.230E+03
3.317E-03	1.338E-01	7.976E+00	9.603E+00	4.566E+01	2.875E+03
5.945E-03	1.724E-01	7.410E+00	8.369E+00	4.142E+01	2.621E+03
1.066E-02	2.194E-01	5.738E+00	4.638E+00	2.606E+01	1.693E+03
1.910E-02	2.846E-01	5.969E+00	5.069E+00	2.949E+01	1.939E+03
3.424E-02	3.641E-01	5.796E+00	5.214E+00	3.170E+01	2.105E+03
6.137E-02	4.354E-01	5.262E+00	5.078E+00	3.281E+01	2.197E+03
1.100E-01	4.253E-01	2.913E+00	3.566E+00	2.784E+01	1.905E+03
1.972E-01	3.837E-01	3.171E+00	3.931E+00	3.154E+01	2.138E+03
3.534E-01	3.506E-01	3.401E+00	4.228E+00	3.542E+01	2.365E+03
6.335E-01	3.223E-01	3.583E+00	4.495E+00	3.968E+01	2.608E+03
1.136E+00	2.988E-01	3.595E+00	4.620E+00	4.286E+01	2.783E+03
2.035E+00	2.756E-01	3.165E+00	4.228E+00	4.211E+01	2.691E+03
3.648E+00	2.466E-01	2.102E+00	2.922E+00	3.432E+01	2.111E+03
6.539E+00	2.198E-01	1.769E+00	2.436E+00	3.037E+01	1.844E+03
1.172E+01	1.750E-01	1.343E+00	1.628E+00	2.274E+01	1.344E+03
2.101E+01	1.369E-01	1.042E+00	1.226E+00	1.782E+01	1.044E+03
3.766E+01	5.092E-02	5.002E-01	5.895E-01	8.578E+00	5.023E+02
6.750E+01	3.854E-05	2.545E-04	1.506E-04	2.882E-03	1.566E-01
Maximum:	0.44	9.1	13	61	4000

Table 8. Heavy-Ion LET Spectra; Ratios to Petersen Environment. Worst-case composition - event fluence - 1 g/cm^2 shielding.

LET (MeV/μm)	Galactic	IMP-8	Ordinary	90% WC	AL
	Exposure Equivalent to 1 Day in Petersen Environment (days)				
1.000E-04	2.336E-02	2.468E+00	1.447E+01	6.532E+01	4.379E+03
1.792E-04	3.291E-02	2.785E+00	1.508E+01	6.783E+01	4.509E+03
3.213E-04	4.515E-02	3.061E+00	1.535E+01	6.922E+01	4.549E+03
5.759E-04	6.081E-02	3.240E+00	1.516E+01	6.914E+01	4.476E+03
1.032E-03	7.833E-02	3.339E+00	1.467E+01	6.835E+01	4.364E+03
1.850E-03	1.021E-01	3.359E+00	1.365E+01	6.591E+01	4.177E+03
3.317E-03	1.338E-01	3.432E+00	1.259E+01	6.438E+01	4.081E+03
5.945E-03	1.724E-01	3.666E+00	1.202E+01	6.625E+01	4.236E+03
1.066E-02	2.194E-01	3.754E+00	9.272E+00	5.909E+01	3.871E+03
1.910E-02	2.846E-01	4.705E+00	1.096E+01	7.249E+01	4.800E+03
3.424E-02	3.641E-01	5.899E+00	1.229E+01	8.513E+01	5.672E+03
6.137E-02	4.354E-01	7.577E+00	1.323E+01	9.722E+01	6.489E+03
1.100E-01	4.253E-01	9.423E+00	1.211E+01	1.013E+02	6.780E+03
1.972E-01	3.837E-01	1.312E+01	1.375E+01	1.194E+02	7.893E+03
3.534E-01	3.506E-01	1.763E+01	1.526E+01	1.402E+02	9.096E+03
6.335E-01	3.223E-01	2.227E+01	1.682E+01	1.646E+02	1.049E+04
1.136E+00	2.988E-01	2.605E+01	1.804E+01	1.857E+02	1.171E+04
2.035E+00	2.756E-01	2.817E+01	1.768E+01	1.923E+02	1.200E+04
3.648E+00	2.466E-01	2.815E+01	1.392E+01	1.713E+02	1.041E+04
6.539E+00	2.198E-01	2.759E+01	1.218E+01	1.569E+02	9.446E+03
1.172E+01	1.750E-01	2.527E+01	8.827E+00	1.242E+02	7.329E+03
2.101E+01	1.369E-01	2.160E+01	6.827E+00	9.924E+01	5.813E+03
3.766E+01	5.092E-02	1.065E+01	3.290E+00	4.784E+01	2.802E+03
6.750E+01	3.854E-05	3.267E-02	1.506E-04	2.882E-03	1.566E-01
Maximum:	0.44	28	18	190	12000

daily count of upset rates, calculated from the Petersen method, that may be expected during the course of the event (for the galactic flux an "event" is one day of exposure).

III. APPLICATION OF MODEL LET SPECTRA TO PETERSEN'S FIGURE-OF-MERIT CALCULATION

To apply the integral LET spectra of the previous section to the Petersen figure-of-merit calculation, these spectra must be approximated as

$$F = A \times (\mathrm{LET})^{-2}$$

Because the spectra are not well represented by such a form, the constant A may be selected in a number of different ways. If the LET spectra were well represented by Petersen's assumption of a power-law with index = -2, then the entries in each column of Tables 5 through 8 would be independent of energy. The fact that they are not illustrates the errors inherent in the approximation.

The conservative method is to determine the value of A so that the approximation is equal to or greater than the model LET spectrum at every point. This is equivalent to choosing the *maximum* value in each column of Tables 5 through 8, and this is the choice selected in this report. For any choice of A smaller than this one, it is possible to construct an example wherein the calculated figure-of-merit upset rate would be smaller than the rate calculated from the proper pathlength distribution integral. Thus, without *a priori* knowledge of the types of devices to which this method will be applied, this conservative choice is the best. Table 9 presents a summary of the results of the tables and compares them to other work.

Table 9. Comparison of Model LET Spectra Intensities to the Spectrum Assumed by Petersen et al. (1983). All integral LET spectra are approximated as power laws in LET with exponents of -2.

	Composition Assumed	
	Normal	Heavy-Ion Enriched
Petersen model flux	1.0	
Galactic model flux	0.44	
"IMP-8" flare peak flux	11.0	34.0
"Ordinary" flare peak flux	13.0	31.0
"90% Worst Case" flare peak flux	83.0	180.0
"Anomalously Large" flare peak flux	5000.0	16000.0
Petersen model daily fluence	1.0 day	
Galactic model daily fluence	0.44 days	
"IMP-8" flare fluence	9.0 days	28.0 days
"Ordinary" flare fluence	13.0 days	18.0 days
"90% Worst Case" flare fluence	61.0 days	190.0 days
"Anomalously Large" flare fluence	4000.0 days	12000.0 days
Smith galactic cosmic ray flux models:		
"Adams 90%" flux	0.37	
"Solar minimum" flux	0.29	
"Cycle Average" flux	0.20	
Smith solar flare peak flux models:		
"AL - Mean Composition" peak flux	3300.0	
"OR - Mean" and "90% WC" Comp.	7.9	112.0
Smith solar flare fluence models:		
"AL - Mean Composition"	1540.0 days	
"OR - Mean" and "90% WC" Comp.	5.6 days	78.0 days
AL - as "adjusted" for composition (/2.3) and time-intensity profile (/1.6)	420.0 days	

IV. COMPARISON TO THE RESULTS REPORTED BY E. C. SMITH OF TRW

In a private report of limited circulation, E. C. Smith from TRW has determined a set of multipliers that differ significantly from those derived in the present report. In this section these differences are explored and explained.

Smith examined four cases, all of which assume a passive shielding equivalent to 1 g/cm^2 of aluminum: (1) a solar cycle average environment, (2) an "anomalously large" flare without any heavy-ion enrichment, and two "ordinary"-sized flares that assume (3) a "mean" composition and (4) a "90% worst-case" composition (i.e., a flare with a significant enrichment of heavy ions). The results of Smith's calculations are also summarized in Table 9.

One of the consistent differences between Smith's results and the results reported here is that Smith chose to determine the constant A in the power-law approximation to the LET spectrum by using a weighted average method. (In effect, Smith averaged his equivalents of the entries in each of Tables 5 through 8 over some energy range.) This procedure produces constants that are smaller than the upper-limit conservative choice by a factor ranging from 1.5 to <3. This is all that is necessary to explain the differences between Smith's results for the galactic flux models and those of Tables 1 through 8.

Whether or not this averaging technique is proper or appropriate is a matter of opinion. It is my opinion that it is not. I believe that when such approximations are used to simplify a problem like this one, those approximations should yield error rate estimates that are upper limits. If the upper limit error rate is intolerable, then a more accurate calculation can be made to refine the result. If the approximate result is not based on an upper limit, then the actual error rate may be larger than expected, which may lead to unknown and unaccountable problems in the effectiveness of the system.

Another correction that Smith applied to his results for the galactic flux environment was to divide the solar minimum environment model result by

1.5 as an estimate for a solar cycle average. This is approximately correct, but it is important to remember that it is appropriate only for solar cycle (10 or more years) averages.

For the solar flare models there are several more dramatic differences between Smith's results and those presented here. The difference of a factor of 1.5 between Smith's "AL - Mean Composition" multiplier (3300.0) and the value derived here (5000.0) is due to the selection effect described above. Just as in the galactic cosmic-ray flux multipliers, one part of the explanation for the differences between these flare multipliers may be traced to the choice of how to fit the LET spectra. These differences lead to a consistent bias between the results. There are, however, additional effects.

When comparing results for the flare fluence models, the multipliers are dependent not only on the spectrum fitting technique, but also on assumptions concerning the time-intensity profile of the flare. For the IMP-8 flare the total fluence was measured directly, and from that measurement a time factor (equal to 20 hr) was derived. This time factor is the ratio of the total fluence divided by the peak event flux. In contrast, the Adams models provide separate spectra for peak flux and event fluence for each of the flare cases. To obtain his result for an anamolously large flare model, Smith assumed a time factor of 11.08 hr. The justification for this choice is not documented, but compared to the Adams model result it produces a spectrum smaller by a factor of 2.6 (1540 days rather than 4000 days equivalent exposure relative to the Petersen environment).

The most serious problem with Smith's analysis concerns the corrections that he applies to his AL flare multiplier to account for deficiencies that he finds in the models. In an appendix, Smith declares that the model overestimates the proton fluence observed in the August, 1972 flare by a factor of 1.6 and that the heavy-ion abundance was overestimated by a factor of 2.3. Together these factors serve to reduce Smith's result from 1540 days to 420 days. Combined with the factor of 2.7 difference cited above, these corrections lead Smith to a final result that is only 10% of the Adams model prediction.

While Smith may argue that his corrections can be justified by a specific event, it is not clear that they are appropriate in a generic model. This conflict raises a policy question like that of fitting the LET spectrum. Should one adopt a model that has been carefully minimized to suit a particular function, or should one retain a standard model (like that of Adams et al.)? It is important to remember that anomalously large flares are extremely rare, and that the data base that documents the features of these events is extremely limited. The uncertainties of any parameters that seek to describe AL flares as a class are large. The factor of 10 reduction in Smith's value for the "AL flare" multiplier places it at the low end of the range. The significant concern is that, by adopting an optimistic model of the environment, real problems may be ignored rather than solved.

V. RELATIONSHIP OF RESULTS TO OTHER ENVIRONMENT SPECIFICATIONS

The Adams models have received wide circulation. As a result, they have served as the basis for a number of working specifications for model environments. When these other specifications share the same spectral form as the Adams models, it is easy to convert the results of this report to apply to another specification. For example, if one built a model assuming a 10-year environment including five AL flares - one at the intensity of the August, 1972 event, two at one-half that intensity, and two at one-quarter that intensity -, then since this is equivalent to a total of 2.5 times the August, 1972 flare fluence, the total number of upsets from these events can be obtained from a fluence spectrum that is 2.5 times greater that that of Tables 3 or 4. Similarly, other combinations of these standard galactic flux and flare models can be constructed.

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